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Research article

Sex Moderates the Relationship between Perceptual-Motor Function and Single-Leg Squatting Mechanics

Jennifer A. Hogg [1]✉, Jason M. Avedesian [2], Jed A. Diekfuss [3,4,5], Shellie N. Acocello [1], Rylee D. Shimmin [6], Elisabeth A. Kelley [7], Deborah A. Kostrub [8], Gregory D. Myer [3,4,5,9] and Gary B. Wilkerson [1]

[1] Department of Health and Human Performance, The University of Tennessee Chattanooga, Chattanooga, TN, USA; [2] Clemson University Athletic Department, Clemson, SC, USA; [3] Emory Sports Performance And Research Center (SPARC), Flowery Branch, GA, USA; [4] Emory Sports Medicine Center, Atlanta, GA, USA; [5] Department of Orthopaedics, Emory University School of Medicine, Atlanta, GA, USA; [6] University of North Georgia, Dahlonega, GA, USA; [7] Erlanger Sports and Health Institute, Chattanooga, TN, USA; [8] Hughston Clinic Orthopaedics, Nashville, TN, USA; [9] The Micheli Center for Sports Injury Prevention, Waltham, MA, USA

Abstract

To examine the isolated and combined effects of sex and perceptual-motor function on single-leg squatting mechanics in males and females. We employed a cross-sectional design in a research laboratory. Fifty-eight females (22.2 ± 3.5 yrs, 1.60 ± .07 m, 64.1 ± 13.0 kg) and 35 males (23.5 ± 5.0 yrs, 1.80 ± .06m, 84.7 ± 15.3 kg) free from time-loss injury in the six months prior, vertigo, and vestibular conditions participated in this study. Independent variables were sex, perceptual-motor metrics (reaction time, efficiency index, conflict discrepancy), and interaction effects. Dependent variables were peak frontal plane angles of knee projection, ipsilateral trunk flexion, and contralateral pelvic drop during single-leg squatting. After accounting for the sex-specific variance and perceptual-motor function effects on frontal plane squatting kinematics, female sex amplified the associations of: higher reaction time, lower efficiency index, and higher conflict discrepancy with greater right ipsilateral peak trunk lean (R^2 = .13; p = .05); higher reaction time, lower efficiency index, and higher conflict discrepancy with decreased right contralateral pelvic drop (R^2 = .22; p < .001); higher reaction time and lower conflict discrepancy with greater right frontal plane knee projection angle (R^2 = .12; p = .03); and higher reaction time with greater left frontal plane knee projection angle (R^2 = .22; p < .001). Female sex amplified the relationship between perceptual-motor function and two-dimensional frontal plane squatting kinematics. Future work should determine the extent to which perceptual-motor improvements translate to safer movement strategies.

Key words: Flanker, valgus, trunk lean, pelvic drop, anterior cruciate ligament, biomechanics.

Introduction

Sex disparity in the occurrence of anterior cruciate ligament (ACL) injuries is well documented, with females sustaining ACL injuries at 2-5 times the rate as their male counterparts (Montalvo et al., 2019; Bram et al., 2020; Gupta et al., 2020). Females are more likely to sustain noncontact ACL injuries via frontal and transverse plane mechanisms, whereas males more commonly sustain ACL injury as a result of contact with another player (Agel et al., 2016; Gupta et al., 2020). The stark difference in noncontact ACL injury occurrence suggests the suboptimal motor programming in females, resulting in faulty neuromuscular control and subsequent injury. Strong and consistent evidence of kinematic and kinetic differences between males and females (Pollard et al., 2007; Schmitz et al., 2007; Sigward et al., 2014; Cronström et al., 2016; Peebles et al., 2020; Petrovic et al., 2020) have led researchers to seek better understanding of underlying factors for biomechanical discrepancies, most notably resulting in copious investigations into the role of muscle strength and activation in lower extremity biomechanics (Nguyen et al., 2011; Cashman, 2012; Mauntel et al., 2013; Homan et al., 2013; Hollman et al., 2014; Hogg et al., 2021). Despite concerted efforts, there remains a need to better delineate the mechanistic underpinnings of altered biomechanical patterns that increase ACL injury risk in female athletes. Uncovering salient neuromuscular components further upstream (e.g., central nervous system) may elucidate underlying contributors to peripheral biomechanical sex differences.

Perceptual-motor function, or efficient and rapid integration between the central and peripheral nervous system for processing goal-oriented motor output, (Wilkerson et al., 2021b) may contribute to impaired motor control and musculoskeletal injury (Wilkerson et al., 2017). When performing dynamic tasks such as sport-specific maneuvers, perceptual-motor attributes such as reaction time, processing speed, working memory, and muscular coordination allow adaptation to changing environmental conditions and protect musculoskeletal structures during high load scenarios (Swanik, 2015). Slower reaction time and working memory performance have been associated with unstable neuromuscular control patterns (i.e., increased ground reaction forces and greater knee abduction angles/moments) that contribute to musculoskeletal injury occurrence (Avedesian et al., 2021). Although deficits in perceptual-motor function have been demonstrated as risk factors for musculoskeletal injury, (Covassin et al., 2007; Mcdonald et al., 2019) evidence pertaining to sex-specific effects of perceptual-motor function and its relationship to neuromuscular control is sparse (Avedesian et al., 2021). There is compelling evidence arguing that males and females *perceive* stimuli differently, particularly visual stimuli. To illustrate, females are more prone to motion sickness than males following use of a virtual reality headset,

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(Munafo et al., 2017) a predisposition thought to stem from pre-existing sex differences in visual processing and postural control (Koslucher et al., 2016). Sex differences in perception and central nervous system function are documented, (Baumann, 2007) and although motor control behavior in healthy populations are less understood, healthy males display faster simple reaction time females (Dykiert et al., 2012). Whether these sex differences in perception and response equate to meaningful differences in motor control, particularly during a functional task in healthy individuals, is unknown.

Prior studies have used smartboard technology to assess perceptual-motor function (Wilkerson et al., 2017; 2021b). However, such technology may not be readily available for clinical practice due to high cost and space issues, necessitating the development of more feasible devices for perceptual-motor assessment. To meet this need, we recently developed a smartphone application to administer the flanker task, (Eriksen and Eriksen, 1974; Wilkerson et al., 2020) a valid and reliable assessment for capturing perceptual-motor reaction time and accuracy. The flanker task has been used successfully to isolate sex-related differences in perceptual motor function following concussion, (De Beaumont et al., 2009; Pontifex et al., 2009; McGowan et al., 2019) though its use as a clinical indicator of neuromuscular control is unexplored. Therefore, the purpose of this study was to evaluate the moderating effects of sex on the relationship between perceptual-motor function, as measured via our smartphone flanker task app, and two-dimensional lower extremity single-leg squatting biomechanics. Our general hypothesis was that sex would moderate the relationship between perceptual-motor function and lower extremity squat biomechanics. Given that females have greater susceptibility to neuromuscular control errors and non-contact lower extremity injury during dynamic sport, we specifically hypothesized that the relationship between perceptual-motor function and two-dimensional squatting mechanics would be amplified in females.

Methods

Participants

A convenience sample of 93 participants (58 female, 35 male) were recruited for this study. Participant demographics are presented in Table 1.

Table 1. Participant descriptive statistics.

	Females (N = 58)	Males (N = 35)
Age, yrs	22.2 ± 3.5	23.5 ± 5.0
Height, m	1.60 ± .07	1.80 ± .06
Mass, kg	64.1 ± 13.0	84.7 ± 15.3

Specific exclusion criteria were lower extremity injury resulting in time loss from activity within the previous six months, vertigo, or diagnosis of a vestibular condition affecting balance. History of concussion was not an exclusion criterion, as we wanted to capture a sample representative of individuals safely participating in athletic activity. Activity levels were comparable between sexes (χ^2 Fisher's exact $p = .58$), as 85.7% (30/35) of males and 79.3% (46/58) of females reported participation in moderate-to-vigorous physical activity at least three times per week.

Procedures

Following written informed consent, each participant's height and weight were obtained. Each participant was then familiarized to the flanker test and performed a ten-repetition practice trial prior to data collection. Flanker testing was administered via a previously established smartphone app, exhibiting good to excellent reliability for reaction time ($ICC_{2,K} = 0.80$) (Wilkerson et al., 2020). The flanker test consists of a five-arrow configuration of either congruent (< < < < < or > > > > >) or incongruent (< < > < < or > > < > >) repetitions. Briefly, twenty flanker repetitions (10 congruent and 10 incongruent) were presented in a randomized order as participants held the smartphone at elbow height. Each repetition was presented for 300 ms with inter-stimulus intervals ranging between 500-1500 ms. Participants were instructed to rapidly tilt the device in the frontal plane toward the direction corresponding with the center arrow. An audible beep, signifying response completion, was elicited when the angular velocity of the device exceeded 115 degrees per second. A trial was aborted and restarted if no response was registered within two seconds. Congruent with prior work, a single 20 repetition trial was collected and used for analysis (Wilkerson et al., 2020).

Following flanker testing, participants were outfitted with seven retroreflective adhesive markers at the following landmarks: anterior aspect of each ankle midway between the lateral and medial malleoli, center of each patella, each ASIS, and the sternum. Participants performed three single-leg squats on each limb while filmed in the frontal plane by a single camcorder (Canon Vixia HF R700) at 24 Hz. Participants were instructed to keep their hands on their hips and attain approximately 45° of weight-bearing knee flexion with each squat (Munro et al., 2017). Participants were given no other instructions.

Data handling

Reaction time of each repetition, in milliseconds, was extracted from the smartphone flanker app. Reaction time was averaged across all twenty trials to use in subsequent computations and analyses. *Efficiency index* and *conflict discrepancy* were also computed (Wilkerson et al., 2020). Efficiency index represents the reaction time penalized for response inaccuracies and was computed as: reaction time + (reaction time *(1 – proportion response accuracy)). Conflict discrepancy is conceptually similar to the previously reported "interference effect"(De Beaumont et al., 2009; Pontifex et al., 2009; McGowan et al., 2019) and represents the incremental time cost of responding quickly and correctly to incongruent repetitions versus congruent repetitions and was computed as: efficiency index for incongruent repetitions – efficiency index for congruent repetitions. For all three flanker variables, lower numbers indicate better performance.

For the single-leg squats, frontal plane variables of peak trunk lean, peak contralateral pelvic drop, and knee projection (abduction) angle were extracted from the point of maximum knee flexion during each squat repetition using ImageJ software (National Institutes of Health, Bethesda, MD, USA) (Räisänen et al., 2016). The point of maximum knee flexion was operationalized as the first frame in which the participant's knee was at its most descended point. Specifically, peak trunk lean was measured as the angle formed by a vertical reference line and a line from the sternal marker bisecting the left and right ASIS. Pelvic drop was measured as the angle formed by a horizontal reference line and a line connecting the left and right ASIS. Frontal plane knee projection angle was measured as the angle formed by lines from the weightbearing ASIS to the center of the patella to the mid-malleolar marker. Positive angles were denoted as ipsilateral trunk lean, contralateral pelvic drop, and medial knee movement. Three trials were performed on each leg and peak angles were averaged within-leg and subsequently analyzed.

Statistical approach

To determine the influence of sex, perceptual-motor function, and their interactions on 2-dimensional kinematics, backward stepwise (p out > 0.20) sex-moderated regressions were conducted, one for each kinematic variable on each side. Independent variables were entered as individual variables (sex, reaction time, efficiency index, conflict discrepancy) and as interactions (sex*reaction time interaction, sex*efficiency index interaction, and sex*conflict discrepancy interaction). In this way, we were able to determine the extent to which sex partially or fully moderated the relationship between perceptual-motor function and frontal plane squatting mechanics. R^2 values of 0.09 (medium effect) (Cohen, 1988) or greater were considered meaningful. All analyses were conducted in SPSS version 27 (IBM Corp., Armonk, NY).

Ethical considerations

The study protocol and informed consent procedures were approved by the university's Institutional Review Board prior to data collection.

Results

Sex-stratified descriptive statistics for independent and dependent variables are presented in Table 2.

Right leg squatting

After accounting for the direct effects of reaction time (partial p = .07), efficiency index (partial p = .06), and conflict discrepancy (partial p = .15), female sex amplified the relationships of higher reaction time (partial p = .07), lower efficiency index (partial p = .06), higher conflict discrepancy (partial p = .15) with greater ipsilateral peak trunk lean (R^2 = .13; p = .05). After accounting for the direct effects of efficiency index (partial p = .007), female sex amplified the relationships of higher reaction time (partial p = .005), lower efficiency index (partial p = .002), and higher conflict discrepancy (partial p < .001), with decreased contralateral pelvic drop (R^2 = .22; p < .001). After accounting for the direct effects of reaction time (partial p = .04) and efficiency index (partial p = .14), female sex amplified the relationships of higher reaction time (partial p = .002) and lower conflict discrepancy (partial p = .11) with greater frontal plane knee projection angle (R^2 = .12; p = .03).

Left leg squatting

After accounting for the direct effect of reaction time (partial p = .04), being female amplified the relationship of higher reaction time (partial p < .001) with greater frontal plane knee projection angle (R^2 = .22; p < .001). Full results are presented in Table 3.

Table 2. Sex stratified descriptive statistics for independent and dependent variables.

		Females	Males
Independent Variables	Reaction time (ms)	507.0 ± 81.5	488.5 ± 50.9
	Efficiency index*	584.4 ± 135.5	561.4 ± 71.4
	Conflict effect†	289.7 ± 608.4	301.1 ± 300.5
Dependent Variables	Ipsilateral trunk lean (left)	7.7 ± 4.9°	10.3 ± 7.6°
	Ipsilateral trunk lean (right)	7.4 ± 4.6°	10.8 ± 7.5°
	Contralateral pelvic tilt (left)	7.6 ± 5.1°	6.5 ± 4.4°
	Contralateral pelvic tilt (right)	6.5 ± 4.9°	5.9 ± 5.8°
	Frontal plane knee angle (left)	16.5 ± 7.9°	8.1 ± 8.8°
	Frontal plane knee angle (right)	18.6 ± 9.3°	13.3 ± 8.5°

*Efficiency index = reaction time + (reaction time *(1 – percentage response accuracy))
†Conflict effect = efficiency index for incongruent repetitions – efficiency index for congruent repetitions

Table 3. Sex-stratified backward stepwise regression (p out < .2) results detailing the moderating effects of sex on the relationship between perceptual-motor function and 2-dimensional kinematics.

				Part correlations						
Dependent variable	Side	R^2	P value	Sex	Reaction time	Efficiency index	Conflict effect	Sex* Reaction time	Sex* Efficiency index	Sex* Conflict effect
Ipsilateral trunk	R	.13	.05	--	-.194	.200	-.155	.193	-.201	.155
lean (+)	L	.08	.02	--	-.146	--	--	--	-.189	--
Contralateral	R	.22	<.001	--	--	-.284	--	-.295	.320	-.410
pelvic drop(+)	L	.08	.06	.217	--	--	--	-.182	--	-.208
Frontal plane knee	R	.12	.03	--	-.214	.157	--	.328	--	-.170
angle (+)	L	.22	<.001	--	-.213	--	--	.465	--	--

R = right; L = left

Discussion

The purpose of this study was to examine the isolated and combined influences of sex and perceptual-motor function on two-dimensional single-leg squatting mechanics in healthy individuals. To our knowledge, this paper is the first to use sex as a moderating variable to inspect the relationship between perceptual-motor function and biomechanics. Our hypothesis that poor perceptual-motor function in females would correspond with exacerbated squatting mechanics compared with males of similar perceptual-motor function was partially supported. Sex did moderate the relationship between perceptual-motor performance and single-leg squatting mechanics, though the directionality of the observed relationships differed between sexes and warrant further discussion.

Compared to males, females are known to exhibit slower simple reaction times by ~10-15 ms (Dykiert et al., 2012) and greater frontal plane knee movement during dynamic tasks (Cronström et al., 2016). The current data align; females displayed reaction times ~20 ms slower than males, poorer efficiency indices, and more medially projected frontal plane knee angles. Additionally, females have been documented as having greater neurocognitive (Covassin et al., 2007) and structural variability (Nguyen and Shultz, 2007) than males, which our data also support.

Moreover, reports have documented linkages between poor perceptual-motor constructs (i.e., complex reaction time and visual-spatial memory) with greater knee abduction angle during sidestep cutting (Monfort et al., 2019) and drop-jump landing tasks (Herman and Barth, 2016). However, it remains unclear whether sub-optimal movement is being driven by biological sex or by perceptual-motor function. Our data indicate that the combination of these variables is more salient than either variable in isolation. Although quicker reaction time and worse accuracy (efficiency index) were minimally correlated with greater ipsilateral trunk lean and frontal plane knee angles, sex amplified these relationships, such that females with slower reaction time and favorable efficiency index associated with greater ipsilateral trunk lean, greater frontal plane knee projection angle, and less pelvic drop. Interestingly, males and females adopted differing squat movement strategies, as evidenced by the opposing directional relationships for the sex by reaction time interaction effect between pelvic drop and frontal plane knee angle (Table 3). Specifically, these part correlations indicate that females with slower reaction times tended to exhibit greater frontal plane knee projection angles and trunk lean, while males with slower reaction times (but greater accuracy) tended to exhibit greater contralateral pelvic drop. Though previous evidence addressing this specific relationship is limited, females are known to rely on ligamentous knee restraints via knee-trunk coupling during single-leg movement (Hewett and Myer, 2011); Hewett et al., 2002) and males are thought to adopt more proximal control strategies of the trunk and hip, (Alentorn-Geli et al., 2014) which likely explains these respective movement patterns.

We employed a complex discriminative reaction time measure in which participants were required to quickly perceive the stimulus direction and choose one of two possible directional motor responses (Jensen, 2006; Eckner et al., 2015). Though not conclusive, our data indicate that, when considering perceptual-motor function in isolation, participants who displayed more risky movement exhibited quicker reaction times but worse accuracy, a pattern revealed as negative correlations between reaction time and 2D biomechanics and positive correlations between efficiency index and 2D biomechanics (Table 3). The speed-accuracy tradeoff (i.e., Fitts' Law) is a well-established motor learning principle (Fitts, 1954) and an important distinction to make with regards to biomechanics and musculoskeletal injury risk. Simple reaction time has repeatedly been associated with lower extremity biomechanics, (Herman and Barth, 2016; Almonroeder et al., 2018; Monfort et al., 2019; Avedesian et al., 2021) but evidence addressing the role of *accuracy* during complex reaction time tasks is limited. Choice reaction time has discriminated between participants displaying high and low knee abduction angles (Herman and Barth, 2016); additionally, healthy participants have demonstrated slower discriminative reaction times, while injured patients exhibit quicker choice responses (Etemadi et al., 2016), further suggesting meaningful interplay between speed, accuracy, and neuromuscular function (Burcal et al., 2019). Thus, it seems that decrements in cognitive and/or motor accuracy may be reflective of decrements in gross biomechanical accuracy, but continued research is needed to isolate the specific effects of accuracy versus reaction time.

The current results demonstrate that when accounting for perceptual-motor performance, sex is not an independent predictor of single-leg squatting mechanics. Rather, the joint relationship between sex and perceptual-motor function operate synergistically to explain the greatest amount of variance in lower-extremity kinematics. In other words, the sex-moderated relationships detailed in the current report reveal a conditional relationship between perceptual-motor function and 2D biomechanics (e.g., "*If* sex is female, *then* slower reaction time is correlated with greater frontal plane knee angle"). Given that it is unlikely for one single factor to explain the majority of variance in individual biomechanical differences, our data align with the concept of 'state dependence' recently illuminated in sports medicine research. State dependence postulates that the state of a complex system, whether stable or unstable, dictates the extent to which any given deficit may upset the inherent stability (Stern et al., 2021). For example, the likelihood of a musculoskeletal injury occurring in a female could be dependent upon the *state* of the motor control system (Hegedus et al., 2016), such that a well-conditioned motor control system may negate the effects of a previous injury or structural anomalies often associated with injuries in females. This finding is promising for clinicians seeking to intervene upon modifiable characteristics, as perceptual-motor function and the motor control system are trainable characteristics (Wilkerson et al., 2017; 2021b).

We elected to use a single-leg squatting task for this study and acknowledge that the observed relationships may be task-dependent. Compared to a double-leg landing task, a single-leg landing task often entails fewer degrees of knee valgus (Hogg et al., 2020), likely because excessive knee valgus during single-limb support is a more unstable strategy. With only one limb in contact with the ground, solutions to remain upright are limited; excessive trunk lean or knee valgus during single-leg support could more easily result in a fall or injury. Conversely, contralateral pelvic tilt is a strategy whereby balance can be maintained during a single-leg task with minimal risk of an adverse event and may be one explanation for males' tendency to manipulate contralateral pelvic tilt. Despite this, females adopted a distal, knee-dominant strategy. Had we employed a more dynamic single-leg task, such as a landing, there is evidence to suggest movement strategies may have skewed more conservatively to accommodate greater task demands (Cronström et al., 2016).

This study is not without limitations. Firstly, as an observational study, we cannot assume that perceptual-motor function is causative, or that changing perceptual-motor function will result in improved lower extremity squatting biomechanics. As an exploratory investigation, we recruited a convenience sample and did not perform an *a priori* power analysis, resulting in unbalanced sex cohorts. Future work should aim to have groups with similar distributions of males and females and larger sample sizes for greater inclusion of additional, potentially relevant variables in the statistical models (e.g., controlling for history of sports-related concussion (Wilkerson et al., 2021a)). Also, we elected to use a single-leg squat, and although we did observe meaningful sex-specific relationships, we acknowledge that a more dynamic task could have yielded alternative results. Although our male and female participants reported similar levels of engagement in moderate-to-vigorous exercise, we cannot be certain that the preferred exercise mode is similar across participants and that everyone routinely completed jumping, cutting, or landing tasks. Nevertheless, an anticipated single-leg squatting task would be reasonably pertinent across a variety of activity types. Similarly, investigating inter-limb relationships based on leg dominance instead of left/right designations could enhance the present findings and should be considered in future work. While it was considered a strength that our flanker test protocol was brief, thus supporting its clinical utility, future investigation into a more extended protocol may provide opportunity to explore other constructs (e.g. cognitive or attentional fatigue). Lastly, we chose to assess frontal plane kinematics in two-dimensional space because frontal plane motion is often associated with injury to the ACL, particularly in females (Hewett et al., 2005; Dingenen et al., 2015). Although two-dimensional frontal plane knee projection angle is reliable (Jambo et al., 2018), it represents a combination of frontal and transverse plane motions, particularly hip rotation (Ageberg et al., 2010). Future work should extend the present methods by employing 3-dimensional motion analysis technologies to determine sex-moderated, comprehensive movement patterns related to perceptual-motor function.

Conclusion

In conclusion, sex moderated the relationship between perceptual-motor function and two-dimensional frontal plane squatting kinematics, such that females with slower reaction times tended to exhibit more medially-projected knee angles, while males with slower reaction times displayed greater contralateral pelvic drop. Being female amplified the relationship between perceptual-motor function and two-dimensional frontal plane squatting kinematics. Future work should determine the extent to which training perceptual-motor function can improve mechanics during dynamic tasks in each sex.

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Key points

- Sex moderated the relationship between perceptual-motor function and biomechanics, such that females with slower reaction times displayed more medially-projected knees, while males with slower reaction times exhibited altered frontal plane pelvic motion.
- Clinically feasible choice reaction time measures can be used as gross indicators of one's propensity for altered single-leg squatting mechanics.
- Future work should investigate the extent to which these relationships can be modified in each sex.

AUTHOR BIOGRAPHY

Jennifer A. HOGG
Employment
Health and Human Performance Department at the University of Tennessee at Chattanooga in Chattanooga, TN, USA
Degree
PhD, ATC
Research interests
Role of biological sex as it pertains to lower extremity biomechanics and learning
E-mail: jennifer-hogg@utc.edu

Jason M. AVEDESIAN
Employment
Director of Sports Science – Olympic Sports for the Clemson University Athletic Department in Clemson, SC, USA
Degree
PhD
Research interests
Sensorimotor contributions to athlete performance and injury, sports-related concussion, and ACL injury.
E-mail: javedes@clemson.edu

Jed A. DIEKFUSS
Employment
Assistant Professor of Orthopaedics at Emory University in Flowery Branch, GA, USA.
Degree
PhD
Research interests
To optimize sport injury prevention via integration of motor learning principles that target neural mechanisms.
E-mail: Jed.a.diekfuss@emory.edu

Shellie N. ACOCELLO
Employment
Associate Professor and Program Director of the Graduate Athletic Training Program in the Health and Human Performance Department at the University of Tennessee at Chattanooga in Chattanooga, TN, USA.
Degree
PhD, ATC
Research interests
Sequalae of concussions as it pertains to musculoskeletal injury risk.
E-mail: Shellie-acocello@utc.edu

Rylee D. SHIMMIN
Employment
University of North Georgia in Dahlonega, GA, USA.
Degree
MS, ATC
Research interests
The relevance of brain functional connectivity to lower extremity musculoskeletal injury risk.
E-mail: ryleedshimmin@gmail.com

Elisabeth A. KELLEY
Employment
Erlanger Sports and Health Institute in Chattanooga, TN, USA.
Degree
MS, ATC
E-mail: Kelleye315@gmail.com

Deborah A. KOSTRUB
Employment
Hughston Clinic Orthopaedics in Nashville, TN, USA.
Degree
MS, ATC
E-mail: Deborah.kostrub@gmail.com

Gregory D. MYER
Employment
Director of Emory University's Sports Performance and Research Center (SPARC) in Flowery Branch, GA, USA and is a Professor in the Department of Orthopaedics and Emory University in Atlanta, GA, USA.
Degree
PhD, CSCS
Research interests
To understand mechanical and functional deficits associated with athletes at risk for ACL injury and to develop effective clinical interventions to improve life-long outcomes in active individuals.
E-mail: Greg.myer@emory.edu

Gary B. WILKERSON
Employment
Graduate Athletic Training Program of the Health and Human Performance Department at the University of Tennessee at Chattanooga in Chattanooga, TN, USA **D**
egree
EdD, ATC
Research interests
The relevance of brain functional connectivity to lower extremity musculoskeletal injury risk.
E-mail: Gary-wilkerson@utc.edu

✉ **Jennifer A. Hogg, PhD**
University of Tennessee Chattanooga, 615 McCallie Ave., Chattanooga, TN, 37403, USA.